Advantages of a Modular Mars Surface Habitat Approach

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Early crewed Mars mission concepts developed by the National Aeronautics and Space Administration (NASA) assumed a single, large habitat would house six crew members for a 500-day Mars surface stay. At the end of the first mission, all surface equipment—including the habitat—would be abandoned and the process would be repeated at a different Martian landing site. This work was documented in a series of NASA publications culminating with the Mars Design Reference Architecture 5.0. More recent work, dubbed the Evolvable Mars Campaign (EMC), explored whether re-using surface equipment at a single landing site could be more affordable than the Apollo-style explore-abandon-repeat mission cadence. Initial EMC assumptions preserved the single, monolithic habitat—the only difference being a new requirement to reuse the surface habitat for multiple expedition crews. A trade study comparing a single large habitat versus smaller, modular habitats leaned towards the monolithic approach as more mass-efficient. More recent work has focused on the operational aspects of building up Mars surface infrastructure over multiple missions, and has identified compelling advantages of a modular approach that should be considered before making a final decision. This paper explores Mars surface mission operational concepts and integrated system analysis, and presents an argument for the modular habitat approach.

I. Nomenclature

kg	=	kilogram
km	=	kilometer
kWe	=	kilo Watt (electric)
m	=	meter
m^3	=	cubic meters
t	=	metric ton

II. Introduction

ONE unique aspect that distinguishes human Mars exploration architecture from robotic science missions is the need for crew habitation. The functional requirements for an Earth-Mars transit habitat or a Mars surface habitat will be influenced by the number of crew, how long the journey to/from Mars takes, how long they plan to stay on Mars, and what they hope to accomplish there. Mission scenarios studied by the National Aeronautics and Space Administration (NASA) over the past 50 years span a range of options, but typically assume three to six crew per expedition, assume at least six months travel time—each way—between Earth and Mars, with surface stays varying from a few days to more than 500 days depending on mission objectives and trajectories. Beyond these basic mission attributes, there are a large number of decisions to be made when developing human Mars mission habitats, such as: rigid versus inflatable structures; closed versus open life support systems; or modular versus monolithic

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configurations. This paper focuses on the modular versus monolithic decision, including implications to an end-to-end Mars mission architecture.

III. Mars Surface Habitat Evolution

Following the Apollo program's successful human lunar landings, NASA explored a similar approach for Mars. In 1969 Dr. Werner von Braun proposed a 9.1 meter (m) diameter capsule-shaped module, designed to deliver three crew to the surface of Mars (Fig. 1) [1] on a single lander. The lower, descent stage portion would contain crew living quarters, a science laboratory, a one-person unpressurized rover, and consumables for a 30 to 60-day surface stay. As with the Apollo landers, the upper part of the capsule would separate to return crew to Mars orbit. Because the habitat portion served as the ascent launch pad, it would likely be damaged during ascent module lift-off, making this a single-use structure. At the beginning of descent from Mars orbit, the entire capsule—both ascent and descent portions plus crew, consumables, and fluids—was estimated at 43,091 kilograms (kg).

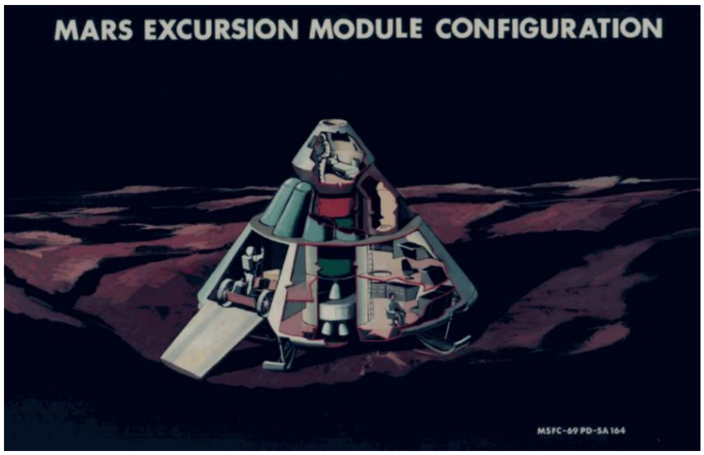

Fig. 1 Werner von Braun Monolithic Mars Excursion Module Configuration (1969)

Development of the International Space Station (ISS) in the 1980's influenced Mars mission concepts towards a more modular habitation approach. A 1985 Manned Mars Mission Working Group study envisioned a reusable surface base to support multiple, four-crew missions [2]. Because the driving requirement for that study was to reduce cost by repurposing existing designs, 4.27 m diameter ISS-type modules were proposed. The authors concluded that a five element "little b" configuration (Fig. 2) was most attractive because the compact footprint would require less effort to level and clear of boulders than other configurations. Concept of operations was limited to moving and configuring elements, with no discussion of what the crew would land in or live in during base assembly, how many landers might be required, or mass estimates for outfitted modules.

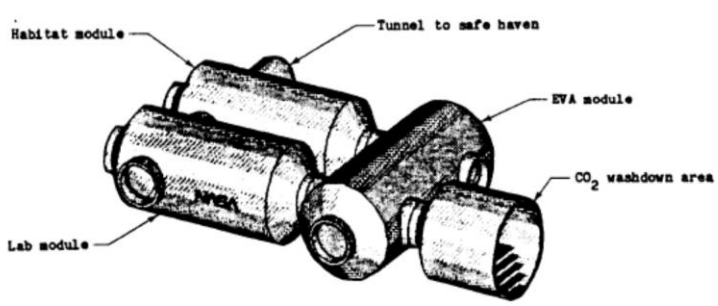

Fig. 2. "Little b" Modular Mars Surface Habitat Configuration (1985)

NASA's first published Mars design reference mission [3] continued the single-base theme, but explored a single, large cabin for both in-space transit and surface habitation. Three cargo missions would deliver equipment—including a surface laboratory of common design to the habitat, plus a Mars Ascent Vehicle (MAV)—before the first six-crew expedition descended and landed in a transit/surface habitat. One key difference between this and Dr. von Braun's earlier approach was the idea of separating the ascent vehicle from the habitat onto different landers. This separation prevented the MAV from damaging the habitat, thus allowing habitat re-use between expeditions, though at the penalty of requiring more landers per expedition. Separating the MAV from the crew ushered in another innovation in this reference mission: the use of an In Situ Resource Utilization (ISRU) plant to produce MAV oxygen propellant, dramatically lowering MAV landed mass.

Once on the surface, the wheeled lander would reposition the 7.5 m diameter habitat to be physically connected with the surface laboratory as shown in Fig. 3, doubling the usable pressurized volume to approximately 1,000 cubic meter (m^3) for the 600-day surface mission. Following the first crew's departure aboard their MAV, two cargo landers would deliver more equipment before the second expedition crew arrived in a fresh transit/surface habitat, adding an additional 500 m^3 pressurized volume with each subsequent mission. Habitat dry mass (structures and equipment) was estimated at about 29,400 kg; with crew, fluids, and consumables the landed "wet" mass was estimated at 53,900 kg. As with the 1985 concept, this was in effect a modular scheme, though with much larger modules. Given that each habitat was sized to house six crew, this approach would have resulted in a very large pressurized volume after just a few expeditions.

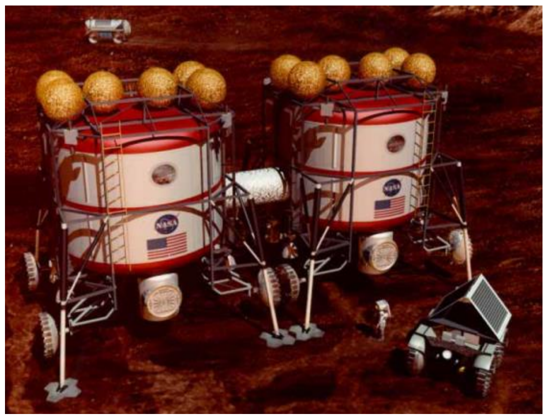

Fig. 3. Modular Mars Surface Habitat and Laboratory (1997)

In 2009, Mars Design Reference Architecture (DRA) 5.0 [4] revisited Dr. von Braun's concept of one-time missions to different landing sites, but paired with the 1997 idea of separate MAV and habitat landers to support an extended surface mission of roughly 500 days for six crew. This concept featured two 40 t payload-capacity landers per expedition and favored a single monolithic habitat estimated at 23,000 kg. Pressurized volume was estimated at between 154 and 198 m^3. Operationally, this scheme offered a chance to explore multiple regions of Mars but, as with the Apollo program, abandoning landed mass at each landing site may not have been sustainable over the long term.

Between 2014 and 2016, NASA's Evolvable Mars Campaign (EMC) [5] explored more affordable solutions, focusing on the single landing site approach and a Field Station built up over multiple expeditions, using much smaller, 20 t payload-capacity landers. After considering both modular and monolithic concepts [6] that study settled on a 7.2 m diameter, 172 m^3 pressurized volume monolithic habitat to support four crew for up to 550-day surface stays. However, two issues were encountered. First, the original 29,479 kg estimated wet mass was trimmed back to a smaller dry mass to fit onto the 20 t payload capacity lander. Second, even if the first expedition crew landed in the partially outfitted habitat, the question remained: what would subsequent crews land in? Deploying a new, large habitat with every expedition was unnecessary but adding a new, smaller element for subsequent crews to land in entailed more development cost. Some thought was given to using the MAV for both crew ascent and descent but ruled out because doing so would drive mass increases across the rest of the architecture [7]. The EMC study settled on landing Expedition 2 and subsequent crews in a 3 t descent cabin, from which they would transfer to the monolithic habitat. However, crew sensorimotor research [8,9] showing that physiological changes during the long microgravity transit to Mars could render crews more susceptible to falls or impair ability to operate equipment shortly after landing posed a dilemma: immediate EVA transfer from a lander may be risky, but remaining in the descent cabin for a post-landing recovery period would drive descent cabin functional requirements and mass.

NASA's Mars Study Capability (MSC) team picked up the challenge in 2017, keeping the EMC Field Station build-up approach, but opting to spread the habitation function across smaller, dual-purpose modules rather than concentrating it into one large, single-purpose habitat. Crew would land in a Logistics Module-sized Descent Module, which would then become a habitable surface module. A stand-alone, four-hatch Airlock Module would serve as the cornerstone of a modular surface infrastructure. The post-landing physiological concern was addressed by the use of inflatable connecting tunnels that allowed shirt-sleeve crew transfer between their Descent Module and a pressurized rover (capable of autonomous operations) for delivery to the Field Station, without having to perform a spacewalk to leave the lander. MSC incorporated a low-energy, hybrid in-space transit architecture [10] that shifted more of the mission duration to Earth-Mars transit, decreasing surface stay to approximately 300 days per expedition, and adopted MAV rendezvous schemes [11] requiring a 22 t payload lander capacity. The net effect of these changes was that fewer landers were required relative to the EMC concept, and landed mass over a three-expedition campaign was lower than all but the von Braun mission plan.

IV. MSC Mars Field Station Concept

To further mature a Field Station concept employing modular habitation, the MSC Team established a set of functional requirements fit within the larger, integrated mission architecture, identified needed cargo elements, and developed operational concept details.

A. Mars Surface Element Functional Requirements

There are four basic functional requirements for MSC's notional Mars Field Station concept:

1) *Sustain crews of four for up to 300 days* - requires habitable volumes, consumables such as food, oxygen, medicine, and spare parts, and utilities such as power, environmental control systems, communications, and waste disposal.
2) *Provide reusable infrastructure* - surface systems must be simple to maintain over long periods of time, robust enough to survive untended quiescent periods of months or years, and accessible to subsequent crews.
3) *Provide a means of exploring at least a 100 km radius from the Field Station* - crews might be able to explore a few kilometers' radius on foot, but traveling 100 km will require surface mobility systems capable of sustaining crews on overnight trips.
4) *Provide a means of returning crew from the Mars surface to Mars orbit* – ascent systems must be reliable enough to perform on short notice, with limited pre-flight testing or repair capabilities, after sitting in quiescent stand-by mode for long periods of time. As part of a comprehensive planetary protection strategy, ascent systems may also be required to help prevent Martian contamination from returning to Earth [12].

B. Mars Surface Mission Elements

Ideally, each surface element will serve multiple purposes and, as much as possible, incorporate common design features to minimize development cost. The study team developed a "standardized" set of elements needed to meet surface mission basic functions (Fig 4).

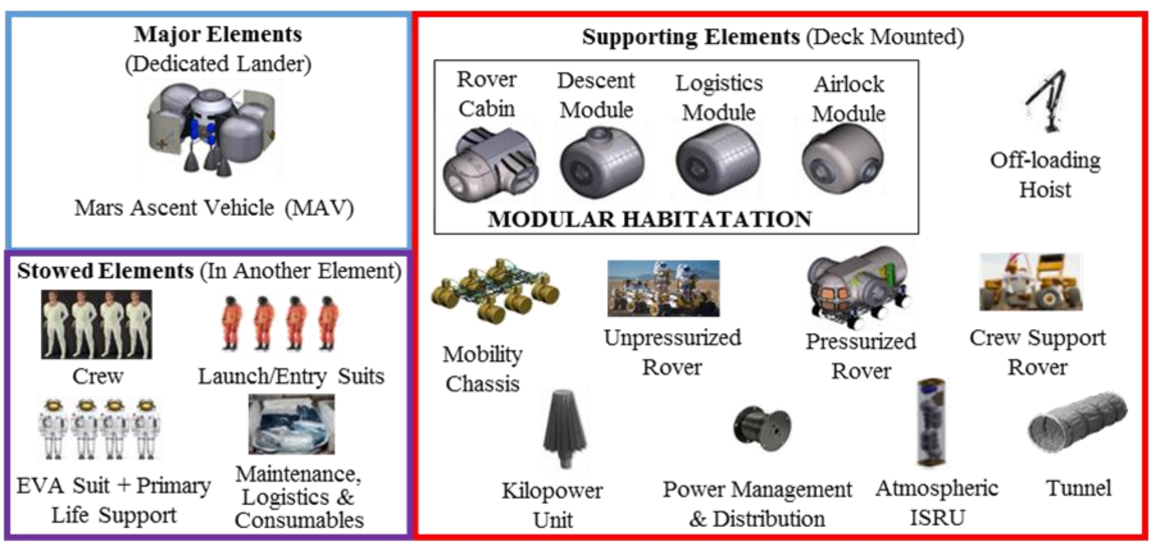

Fig. 4. Notional MSC Mars Surface Elements

Most of these appear in previous works, but this study attempted to streamline the number of unique designs. For example, previous work assumed several different logistics container sizes, whereas this study assumed a single design, sized and scarred for life support systems to allow double-duty as a habitable volume after the logistics resupply task was complete, similar to the Multi-Purpose Logistics Module (MPLM) concept used on the ISS [13]. At 3.8 m diameter by 3.4 m long with a 3,500 kg payload capacity and 25 m^3 habitable volume, the MSC Logistics Container was smaller than an MPLM, but able to fit inside the lander's annular volume between the descent engines [14]. The study team also defined two new elements: a three-hatch Descent Module capable of landing and housing crew for up to 30 days, and a four-hatch Airlock Module that would serve as the cornerstone of a multi-element station. For the sake of commonality (which is thought to reduce overall program costs [15]), the Descent Module was patterned after the Logistics Module shell, with a top-mounted hatch to facilitate crew transfer from the Earth-Mars transit vehicle. To reduce development effort, the Airlock Module could be patterned from a core Pressurized Rover cabin with two additional hatches or from a Logistics or Descent Module shell with additional hatches. Eliminated from this study was the large monolithic habitat and the purpose-built laboratory module (it was assumed that a used Logistics Module could be repurposed as a Laboratory). Some items—such as the MAV—had the benefit of extensive design analysis whereas other elements—such as the Descent or Airlock Modules—were purely notional.

C. Field Station Concept of Operations

MSC adopted the Field Station concept proposed during EMC studies with a three-Expedition campaign approach. Given the MSC-assumed conjunction-class, hybrid propulsion mission cadence [16] of cargo or crew launch opportunities every 26 months, a three-expedition surface infrastructure would need at least a 12-year service life. At that point, a decision would be made whether to extend Field Station life—which may require replacing or refurbishing older infrastructure—or begin a new Field Station elsewhere on the planet.

Expeditions 1 and 2 would each consist of three landers: two cargo landers delivering critical surface infrastructure and a MAV, followed by crew and consumables on a third lander. Only two landers would be needed for Expedition 3: one lander for a MAV, and one lander for crew and consumables. Landers would touch down approximately one kilometer (km) from each other to avoid descent engine plume damage to surface infrastructure. The surface power system and all MAVs would remain on their landers, but all other cargo would be off-loaded onto a mobility chassis using cargo hoists, driven to the Field Station site, and assembled. Two pressurized rovers would allow exploration up to 100 km from the Field Station, and a robotic rover would assist EVA crew and remote telerobotic operations.

Crew would live and work inside a complex of modular habitable spaces, initially arranged in an L-shape as shown in Fig. 5.

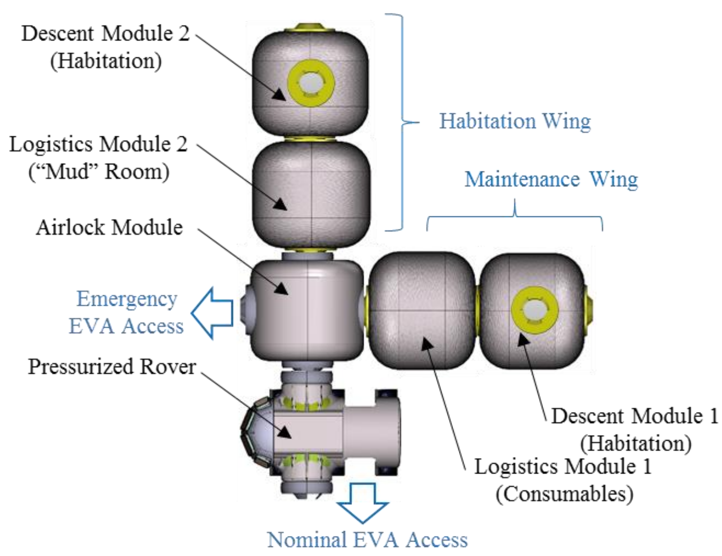

Fig. 5 Notional Expedition 1 Field Station Configuration (Top View)

The four-hatch Airlock Module would anchor the assembly, with a maintenance wing dedicated to noisy activities such as repair parts manufacturing or exercise, and a habitation wing dedicated to quiet activities such as crew sleep or medical consultations. The remaining two Airlock hatches would be used to dock the two pressurized crew rovers or for emergency EVA access. Nominally, spacewalks (or more precisely, Mars walks) would be conducted via suitports [17] on the Pressurized Rovers to minimize the need to open Field Station cabin hatches directly to the Mars surface environment. Descent Modules would serve as the primary habitable spaces but Logistics Modules—as they were emptied of consumables and equipment—could serve as "mud rooms" to further help prevent dust migration back into sleeping quarters. Hatches at the aft modules of each wing provide another emergency egress path, either shirt-sleeve transfer to a docked pressurized rover, or space suited egress via emergency EVA hatch.

For the purpose of this study, each module was assumed capable of providing stand-alone environmental control and life support, but only the Descent Modules would be outfitted for habitability functions such as hygiene and food preparation. Surface power would be connected through the Airlock and distributed to the other modules. Trash would be temporarily stowed in the Logistics Modules. As Logistics Modules accumulate over multiple expeditions, empty modules (not necessarily attached to the stack) would be repurposed for additional capability (e.g., dedicated science/research or manufacturing activities) or designated for long-term storage or trash.

V. MSC Mars Mission Lander Manifests and Field Station Build-Up

A. Manifesting Assumptions

After identifying the equipment needed for Field Station operations over a three-expedition period, the next task was to package it all onto as few landers as possible. A set of manifesting "rules" was developed to ensure that equipment arrived in a logical order. For example, the ISRU system must be co-located on the same lander as the MAV to facilitate MAV propellant production; to ensure crew safety, the MAV must arrive long enough before the crew to allow MAV propellant production time in the event that an emergency forces the crew to depart shortly after landing. The MSC team also added new assumptions to reduce the number of logistics modules needed, such as an ability to stow some cargo inside the MAV's crew cabin, and an assumption that equipment intended for external use (such as a robotic rover), could be lander deck-mounted, rather than stowed inside a Logistics Module. Refer to the Appendix for detailed mission manifests of all eight MSC campaign landers, plus a comparison manifest for the EMC landers.

B. Expedition 1

1. CARGO-1: First Expedition 1 Lander

The first cargo lander of the first crew expedition would be the cornerstone of the entire campaign, anchoring the Field Station site and providing critical infrastructure and landing aids for subsequent landers. As the first of two uncrewed landers before the first crewed landing, this mission would also serve an important risk-reduction role, demonstrating human-scale Mars EDL and autonomous surface operations technologies. The most important cargo delivered with this mission would be surface power infrastructure [18,19] to provide the estimated 40 kiloWatt electric (kWe) service needed to manufacture MAV return propellant, operate the Field Station, and provide recharge power for surface mobility systems. A robotic Crew Support Rover would pre-deploy the power management and distribution system, and meet each subsequent lander to connect it to the surface power grid.

This mission would also deliver a crew Pressurized Rover, as well as the first Descent Module, pre-integrated with a Mobility Chassis. After landing, a Cargo Hoist would grapple and lower the robotic Crew Support Rover, Pressurized Rover, and Descent Module/Mobility Chassis to the surface. The power system would remain on the lander, and the robotic support rover would deploy power cables to subsequent landers.

Though this would be an uncrewed mission, delivering a Descent Module early had two advantages: first, it increased cumulative habitable volume to meet the minimum needed for Expedition 1. Second, it would mitigate risk by providing an opportunity to flight test and verify a Descent Module under actual Mars descent and landing conditions prior to first crew use. This data would provide confirmation that crew descent orientation and landing loads meet safety and health requirements.

2. CARGO-2: Second Expedition 1 Lander

The second cargo lander would deliver the Expedition 1 crew's MAV, an inflatable connecting tunnel, an ISRU system, and power cable. Immediately after touchdown, the Crew Support Rover delivered with the previous lander would drive towards the CARGO-2 lander and robotically connect it to the power grid junction point. Unlike CARGO-1, all payloads on the CARGO-2 lander would remain on-board until after the Expedition 1 crew arrives. Once the lander receives surface power, the ISRU system would begin manufacturing oxygen from atmospheric resources. Oxygen would be liquefied and pumped directly into the MAV's propellant tanks.

3. CREW-1: Third Expedition 1 Lander

Once the MAV's propellant tanks were confirmed full, the third lander of the campaign would deliver the Expedition 1 crew along with consumables and maintenance items. Immediately after touchdown, the Crew Support Rover would drive towards the CREW-1 lander and robotically connect it to the power grid junction point. After months in microgravity, crew are not expected to be medically cleared for EVA until after a physical rehabilitation period of about a week after landing, so they would remain on their lander, with access to the Descent Cabin they landed in plus the Airlock Module and at least one Logistics Container. During this time, the crew would exercise and perform low-impact activities such as cabin reconfiguration and tele-robotic operations. Once crew are cleared for EVA duty, CREW-1 cargo would be off-loaded in preparation for Field Station assembly and activation.

After placing and leveling the Airlock module and attaching it to the surface power grid, the crew would tele-robotically unload and assemble the other modules, completing the Expedition 1 Field Station configuration (Fig. 5). The priorities for this first expeditionary crew are to assemble the initial Field Station infrastructure, deploy autonomous sensing equipment, collect crew health data during exposure to the Mars environment, and conduct science experiments. Because much of the cargo allocation would be dedicated to surface infrastructure build-up rather than consumables mass, the first expedition's surface stay duration would be shorter—only about 163 days, compared to 300 days for subsequent expeditions. This would require the crew to spend more time in Mars orbit than on subsequent missions. Expedition 1 would also have relatively little unallocated mass as compared to subsequent missions. The Expedition 1 crew would have at their disposal a total pressurized volume estimated at about 167 cubic meters (m^3). Depending on how the Logistics Containers are used once empty, this could be as much as 135.8 m^3 of total habitable volume (almost 34 m^3 per crew), which is likely to be more than the Earth-Mars transit habitat would offer. Expedition 1 would also carry one metric ton of science payload.

C. Expedition 2

The lander cadence for Expedition 2 would be identical to Expedition 1: CARGO-3 and CARGO-4 would deliver Field Station infrastructure items and a MAV, then CREW-2 would deliver the Expedition 2 crew and consumables. The Expedition 2 crew would land in another Descent Module, integrated to at least one Logistics Module and an inflatable transfer tunnel. As noted above, Expedition 2 crew could perform a pressurized intravehicular (IVA) transfer to the Pressurized Rover and be autonomously delivered to the Field Station. With no need to bring another surface power system or Airlock Module, Expedition 2 landers could deliver more consumables mass, allowing for a longer surface stay. This in turn would allow Expedition 2 time and resources to extend their exploration footprint farther from the Field Station.

When added to the approximately 167 m^3 of pressurized volume delivered during Expedition 1, the Expedition 2 crew would have as much as 334 m^3 pressurized volume at their disposal. Depending on how the Logistics Containers were used once empty, total habitable volume may be as much as 271.6 m^3.

Note that Expedition 2 landers would have considerably more unallocated mass capacity than Expedition 1, with over eight metric tons unallocated on the second cargo lander and nearly two metric tons on the crew lander. Unallocated mass could be used for "get-ahead" logistics for subsequent expeditions, but the long lag time between crews makes this impractical for shelf life-limited consumables such as food. For the purpose of the initial concept of operations, the unallocated mass is reserved to accommodate potential mass growth due to lessons learned during Expedition 1.

D. Expedition 3

With significant surface infrastructure awaiting them, Expedition 3 could technically be completed with only two landers: CARGO-5 delivering the third MAV, followed by CREW-3 delivering the third expeditionary crew and several Logistics Modules. If maintaining a 3 Lander-per-Expedition cadence, this would allow considerable flexibility for the third expedition, or an opportunity to replace end-of-life infrastructure if extending the Field Station life. Operations for these landers are virtually the same as outlined above for the CARGO-4 and CREW-2 landers. The proposed Field Station configuration at the end of Expedition 3 is shown in Fig. 6.

VI. Discussion

A. Advantages of a Modular Habitat Approach

The most compelling advantage of a modular habitat approach is that it eliminates a key Mars lander size driver. As the largest—and potentially the heaviest—Mars surface element, a long-duration, fully outfitted, 4-crew monolithic

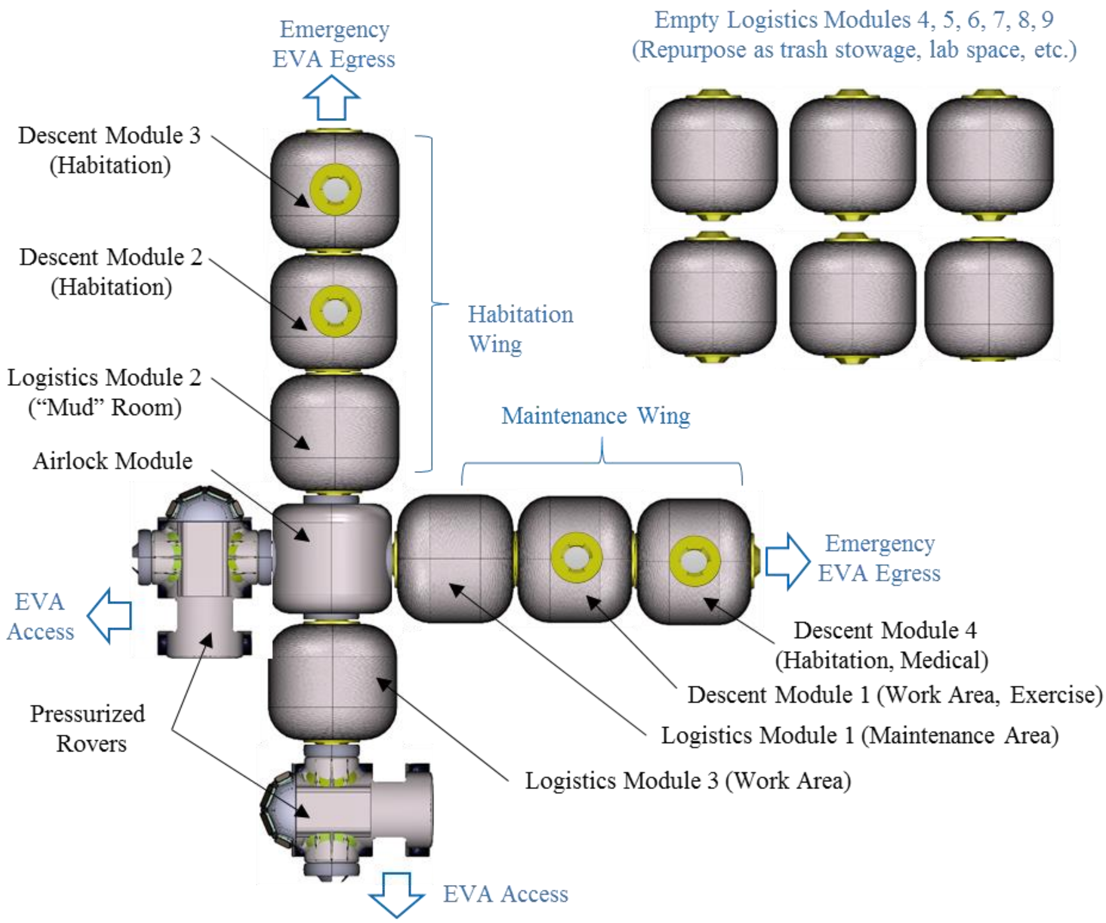

Fig. 6 Notional Expedition 3 Field Station Configuration (Top View)

habitat simply will not fit onto a small lander. Potential mass growth of a monolithic habitat increases risk of the payload exceeding integrated landing system performance, thus forcing a sort of modularization anyway. A large habitat could land partially outfitted, though this complicates its ability to sustain crew until outfitting is complete. The ability to fit onto smaller landers opens up new possibilities for payload co-manifesting on Earth launch systems, or more opportunities for international or commercial investment in smaller launch or landing systems.

Another key advantage of a modular habitat approach is risk reduction and operational flexibility. A monolithic habitat landing off-course—with no way to relocate such a large item—would result in loss of a DRA 5.0 style mission, or loss of at least the first EMC-style expeditionary mission, and would redirect subsequent Field Station buildup to the off-course habitat site (or would require a new lander deliver a new habitat to the intended site, thus delaying the mission). Smaller modules, designed to be off-loaded and relocated, could accommodate several kilometers of off-course landing and offer crew self-rescue options (such as robotic off-loading and relocation of their Descent Module) not previously considered. A larger mobility chassis capable of relocating a 20+ metric ton payload could be manifested to mitigate monolithic habitat risk, but this would add more mass for a contingency transport than the estimated 600 kg for crane-type cargo handlers to lift 6 to 8 t modules. Risk is further reduced by spreading habitability across multiple, redundant compartments, any one of which could be isolated and removed from the stack in the event of damage. Pressure hatches between modules allow the crew more time to assess and resolve unforeseen issues, such as a pressure shell leak or fire in one module. The MSC scheme further reduces risk by manifesting an uncrewed Descent Module on the first of two uncrewed landers to fully verify landing safety prior to crew first use.

From a habitability point of view, individual modules are ideal for isolating dirty or noisy activities, such as exercise or manufacturing, from clean or quiet activities, such as crew sleep or medical evaluations. Activity isolation in a monolithic habitat could be done with internal partitions but that adds mass to what is already a large payload. A modular approach potentially offers much larger cumulative habitable volumes than monolithic architectures, with each expedition adding to the volume. This would make long surface stays more comfortable, though potentially with a mass and time penalty to maintain more systems. On the other hand, older modules could simply be retired once systems wear out, and replaced with repurposed logistics or descent modules arriving with subsequent crews. The modular approach facilitates trash management by offering an isolated module that can be relocated when full and replaced with a subsequent empty logistics container. Note that this could also be done with a monolithic habitat, but would require a dedicated habitat port to dock the trash module.

A modular approach facilitates system evolution over time: designers may outfit later modules with updated life support or habitability features as new technologies or materials are developed, similar to the evolution of ISS module systems over time. Whereas development and testing of a very large, complex monolithic habitat may be limited to a few vendors, development of smaller, modular elements could be within reach of newer commercial enterprises, potentially sparking more competition and innovation, particularly if a core element structure was adopted as a standard.

Mission plans that re-visit the same site more than once are essentially modular by definition, because subsequent crews have to land in some sort of habitable element. Although the MSC scheme eliminates monolithic habitat development, it adds a purpose-built airlock module. However, commonality between the airlock shell and other, smaller elements may cost less to develop than the one-off monolithic habitat (which had an incorporated airlock inside it).

Finally, as shown in Table 1, the 3-Expedition Cumulative Landed Mass for the MSC modular habitat scheme is actually *lower* than all but the 1969 von Braun mission concept. The MSC concept only requires 176 t of landed payload over three crew expeditions, as compared to 240 t for the DRA 5 mission architecture—a savings of more than 30%. As an analog for cost, this implies good value for the MSC modular habitat concept, though as discussed below, this may not necessarily be a fair metric for comparison.

Table 1 Mission Concept Comparison

	[*]Mission Concept				
	1969 Von Braun	**1997 SP 6107**	**2009 DRA 5**	**2016 EMC**	**2018 MSC**
Number of Crew per Expedition	3	6	6	4	4
Surface Stay Duration (Days)	90-180	1,800	1,500	1,117	763
Expedition 1	30-60	600	500	210	163
Expedition 2	30-60	600	500	357	300
Expedition 3	30-60	600	500	550	300
3-Expedition Cumulative Crew-Days (*Number of crew) x (surface stay duration)*	**270-540**	**10,800**	**9,000**	**4,468**	**3,052**
Number of Landers	3	8	6	10	8
Expedition 1	1	4	2	4	3
Expedition 2	1	2	2	3	3
Expedition 3	1	2	2	3	2
Payload Capacity per Lander (t)	12.68[†]	65	40	20	22
3-Expedition Cumulative Landed Mass (t) **(***Number of landers) x (payload per lander)*	**38.04**	**520**	**240**	**200**	**176**
Mass per Crew-Day (kg) *(3-Expedition cumulative landed mass (kg)) divided by (3-Expedition cumulative crew-days)*	**140– 70**	**48.1**	**26.6**	**44.8**	**57.7**

B. Disadvantages of a Modular Habitat Approach

The obvious disadvantage of a modular approach is the inherent inefficiency of landing and assembling multiple structures with distributed services, such as thermal control, power distribution, and life support systems, crossing

[*] The 1985 ISS-style modular mission reference does not contain lander information or mass estimates, and is not included in this comparison.

[†] Available reference materials are unclear what percentage of Dr. von Braun's 43.1 T descent mass is landed payload, versus descent stage or propellant mass. Assuming a typical ratio of lander wet mass to lander payload mass of 3.4, landed payload is estimated at about 12.68 T for this comparison.

element boundaries. Although landing and activating a single habitat is obviously more operationally efficient, the monolithic approach does not appear to be more mass efficient for repeated visits to the same site.

Stringing together multiple elements also requires a large footprint, free of obstacles or terrain disruptions. Robotic rovers may be able to remove small boulders and the modules themselves may be able to provide limited self-leveling capability, but if a relatively clear, level area is not readily available, additional cargo mass, power, and time may be needed to groom a Field Station site. Given the potential availability of a fission surface power system, and the lengthy lag time between cargo and crew deliveries, neither the power nor time may be an issue. The scheme outlined above does have some mass margin that could be dedicated to surface-grooming equipment—but that unallocated mass occurs on the second expedition, after the initial Field Station modules have been emplaced. The best mitigation may be to identify a relatively clear area at least large enough to accommodate the small number of Expedition 1 modules, then use unallocated mass on Expedition 2 to groom adjacent areas.

Another disadvantage of the MSC scheme is that all habitable modules must be off-loaded from their landers and relocated, increasing the risk of module damage versus earlier approaches that left a large habitat on its lander. On the other hand, one damaged module would be of much less consequence given the availability of multiple modules, and off-loaded modules placed on or close to the surface reduce crew injury risk by eliminating the need for EVA crew to climb up and down ladders to access a lander-mounted habitat.

Another argument against modular habitats is that it may preclude the possibility of commonality between the surface and transit habitats, but the reality is that there is unlikely to be much commonality between these two very different applications anyway. The surface habitat must be designed for entry heating and landing loads, exposure to surface gravity, atmospheric pressure, the surface thermal environment, and abrasive dust, plus support routine EVA and surface science activities—none of which are required of the transit habitat.

Finally, the modular scheme does add mass burden to the Logistics Module design by forcing it to carry scarring for life support and habitability, though commonality with other habitable elements should lessen the cost impact. This is no different from ISS's modular habitation approach. The development of modular life support and thermal systems may help minimize mass burden associated with interfaces for these systems.

From an integrated architecture point of view, lander packaging must be considered. In a modular scheme, several small elements may be arranged to fit onto a large lander deck (Fig. 7). This potentially makes mass-balancing a lander more challenging than it might be with a single large habitat that could be centered on the lander deck, although the challenge likely must be overcome anyway for cargo landers delivering logistics containers and surface mobility systems together. With no single habitable element directly over the lander's center of gravity, it will be more challenging for the lander's reaction control system to maintain control during landing. However, as noted previously, subsequent expeditions to the same Field Station face the same challenge regardless of habitat type, since subsequent crews would likely land in a smaller descent module, co-manifested with other cargo.

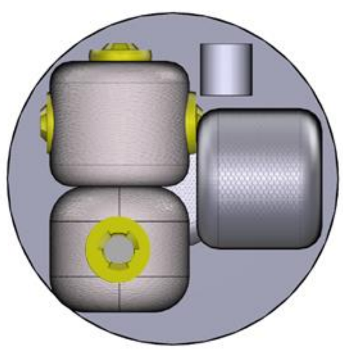

Fig. 7 Notional Lander Deck Packaging with Modular Elements (Top View)

Modular habitation may require more landers and in-space transportation capacity, resulting in higher cost and operational complexity. On the other hand, commonality across a modular architecture may lower design, development, test, and certification cost. At the current level of design fidelity, it is difficult to draw conclusions about how these costs may compare.

C. Mass Comparison of Options

Although the overall landed payload mass for the MSC scheme is lower than most of the other architecture approaches discussed, this is an unfair comparison because all but the von Braun plan put more crew on Mars for longer durations. When normalized by crew-days (landed payload mass divided by the number of crew and cumulative surface stay duration over three expeditions), the von Braun and MSC concepts actually perform the *worst*, requiring more than twice the landed payload per crew-day of the other mission concepts (Fig. 8). If landed mass is an analog for the "cost" of a mission, and crew-days represents the "value" obtained for that cost, the new MSC scheme does not appear to be very good value. Why? Undoubtedly multiple modules with connecting hatches are much less mass-efficient than a single, monolithic habitat, though at current design fidelities it is difficult to gauge by how much. Another factor is that as element and mission concepts have been refined, mass estimates for individual elements have tended to increase, and consumables models have been refined [20, 21]. For example, the six-crew DRA 5.0 monolithic habitat was estimated at 16.5 t, which grew to 19.3 t for a four-crew habitat in the EMC scheme. DRA 5.0 assumed 6 t of consumables per six crew, 500-day surface stay, whereas current MSC consumables models estimate 4.9 t for just four crew staying only 300 days—plus another 2.5 t of maintenance items and spare parts that were not included in the earlier mission concept. Although both the DRA 5 and MSC mission plans make two pressurized rovers available to all crews, the DRA 5.0 pressurized rovers were estimated at 4.8 t each, but the MSC pressurized rovers are more than 6 t. This is likely because mass estimates are getting better as we learn more, but could also be indicative of requirements creep as new mission concepts are developed. The maintenance model used in the MSC analysis is based on the number of pressurized compartments, not size or complexity of those volumes, thus penalizing the modular approach.

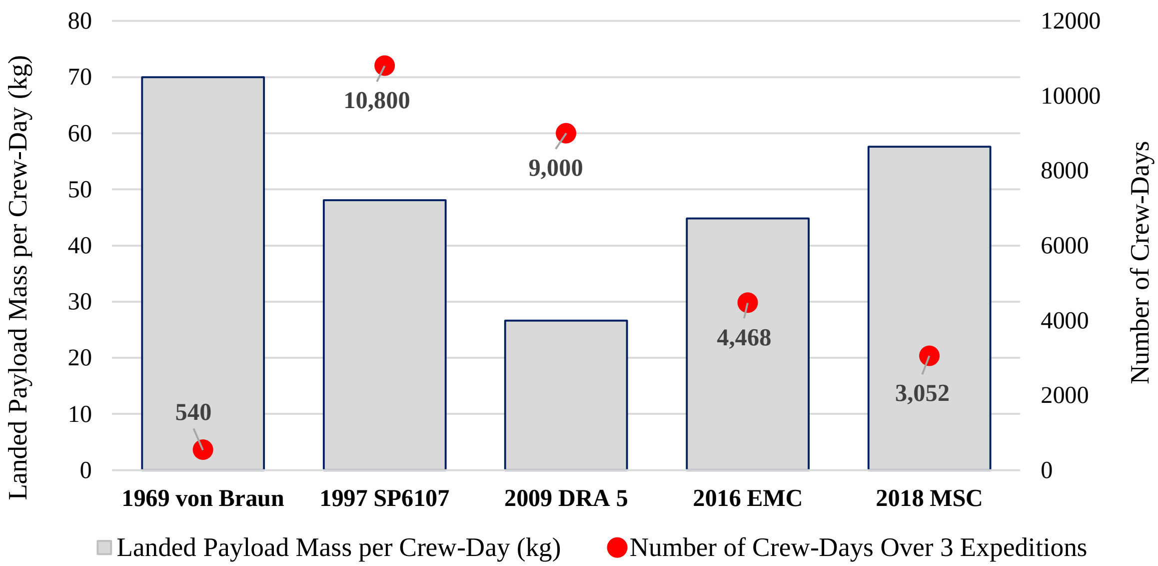

Fig. 8 Mission Concept Comparison

The biggest difference between approaches may be crew surface stay duration, with MSC crews staying half as long as some other plans (due to in-space transportation changes, not habitation limits). Adding consumables mass so MSC crews could remain on Mars for DRA 5.0-like 500-day durations brings landed mass per crew-day lower than the EMC scheme, and becomes much more competitive with DRA 5.0 (Fig. 9). Results were assessed in two ways: first, by utilizing all unallocated mass in the original MSC manifest ("MSC Full Landers" in Fig. 9) and second, by adding a third lander to Expedition 3 for additional consumables ("MSC + 1 Lander" in Fig. 9). Note in-space transportation constraint assumptions would have to be changed to actually accommodate these longer surface stays.

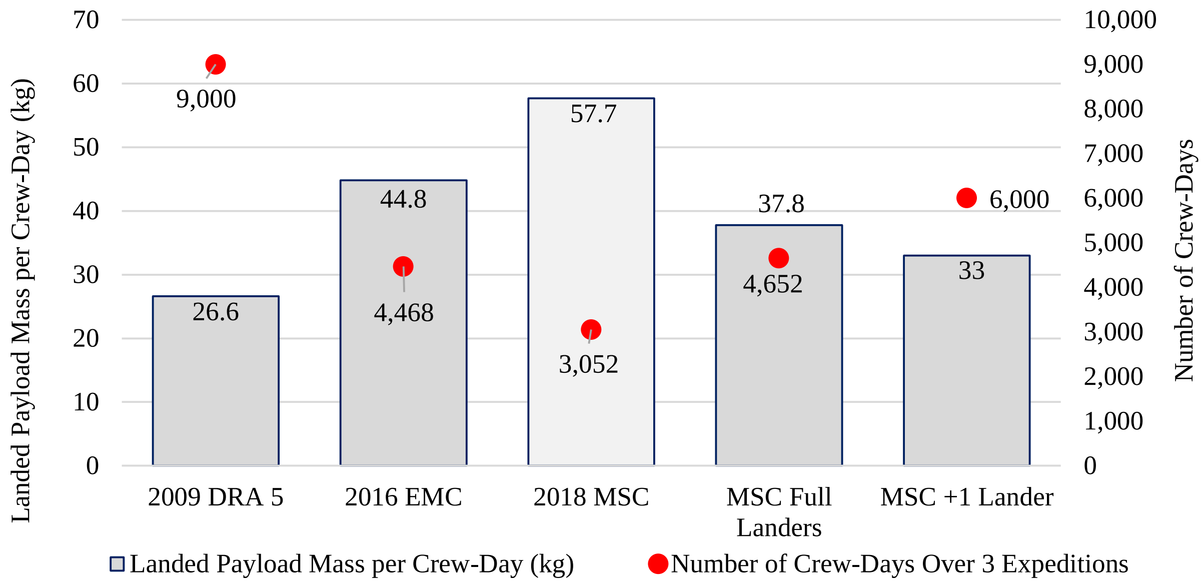

Fig. 9 Effect of Longer Surface Stay Duration on Landed Mass

VII. Conclusions

A monolithic habitat made sense for Apollo-style exploration to a single site, but there are compelling advantages of a modular habitat approach for repeated visits to the same site. Modular habitats offer significant risk reduction and operational flexibility. Development of a large, complex monolithic habitat may be limited to only a few vendors, whereas smaller, modular elements may be within reach of newer start-ups or international partners. Smaller modules fit onto smaller landers, which in turn can fit onto smaller Earth launch systems. Although the MSC modular surface habitat concept does seem to lower cumulative landed payload mass over three expeditions as compared to many previous mission approaches, the MSC concept does not trade as well when normalized for crew-days on the Mars surface. If landed mass per crew day is the mission "value" metric of choice, the MSC scheme could be improved by extending surface stay durations to those assumed in previous architecture plans, though this would require changes to in-space transportation architecture assumptions. This analysis highlights the difficulty in comparing the relative value of mission concepts that appear to be similar, but have very different underlying assumptions.

Appendix

Table A1 Notional MSC Crew Expedition 1 Mission Manifest

	Manifested Items	Mass (kg)	CARGO-1		CARGO-2		CREW-1	
			Exp1 Lander 1		Exp1 Lander 2		Exp1 Lander 3	
			Qty.	Mass	Qty.	Mass	Qty.	Mass
	Crew (each)	100	-	0	--	0	4	400
ISRU	Atmospheric Production Plant	1,032	-	0	1	1,032	-	0
	Part of ISRU radiator mass	478	-	0	1	478	-	0
	ISRU Deployment	130	-	0	1	130	-	0
Power	Kilopower, 10 kWe each	1,544	5	7,720	-	0	-	0
	Power Management/Distribution	400	1	400	1	400	1	400
	Power cable (1 km) spool	70	1	70	1	70	1	70
Robotic	Crew Support Rover (1000 kg chassis + 225 kg robotic assistant)	1,225	1	1,225	-	0	-	0
	Cargo Hoist	600	1	600	-	0	1	600
Habitability	Logistics Module (Dual Hatch, 3500 kg capacity)	2,600	-	0	-	0	2	5,200
	Crew Descent Module	3,516	1	3,516	-	0	1	3,516
	Airlock Module	3,500	-	0	-	0	1	3,500
	Connecting Tunnel	237	-	0	1	237	1	237
	Consumables for up to N sols (4.02 kg/person/sol + 97.57)	Per sol	-	0	-	0	163 sols	2,719
	Spares and Other Logistics (2.946 kg/sol + 2112.9 kg)	Per sol	-	0	-	0	163 sols	2,593
	Maintenance Equipment		-	0	-	0	-	70
EVA	EVA Suit + Primary Life Support System	692.8	-	0	-	0	1	693
	Launch-Entry Assembly Suits	104	-	0	-	0	1	104
	Spares (1.73 kg/sol/crew + 796.8)	4 crew	-	0	-	0	163 sols	1,079
Mobilit	Mars Mobility Chassis	2,457	1	2,457	-	0	-	0
	Crew Outfitting for Chassis	200	-	0	-	0	-	0
	Pressurized Rover	6,021	1	6,021	-	0	-	0
	Allocated Science Payload	1,000	-	0	0.2	200	0.8	800
Transportation	MAV (5 sol, wet)	18,868	-	0	1	18,868	-	0
	Part of MAV Radiator	212	-	0	1	211	-	0
	MPS Tank Cryocoolers/BAC charged to MAV	141	-	0	1	140	-	0
	MDM-to-MAV Adapter	200	-	0	1	200	-	0
	Lander Total Payload Mass (kg)			22,009		21,966		21,981
	Unallocated Mass (kg)			-9		34		19

Table A2 Notional MSC Crew Expedition 2 Mission Manifest

Manifested Items		Mass (kg)	CARGO-3 Exp2 Lander 1		CARGO-4 Exp2 Lander 2		CREW-2 Exp2 Lander 3	
			Qty.	Mass	Qty.	Mass	Qty.	Mass
	Crew (each)	100	-	0	-	0	4	400
ISRU	Atmospheric Production Plant	1,032	1	1,032	-	0	-	0
ISRU	Part of ISRU radiator mass	478	1	478	-	0	-	0
ISRU	ISRU Deployment	130	1	130	-	0	-	0
Power	Kilopower, 10 kWe each	1,544	-	0	-	0	-	0
Power	Power Management/Distribution	400	1	400	1	400	1	400
Power	Power cable (1 km) spool	70	1	70	1	70	1	70
Robotics	Crew Support Rover (1000 kg chassis + 225 kg robotic assistant)	1,225	-	0	-	0	-	0
Robotics	Cargo Hoist	600	-	0	-	0	-	0
Habitability	Logistics Module (Dual Hatch, 3500 kg capacity)	2,600	-	0	1	2,600	3	7,800
Habitability	Crew Descent Module	3,516	-	0	-	0	1	3,516
Habitability	Airlock Module	3,500	-	0	-	0	-	0
Habitability	Connecting Tunnel	237	1	237	-	0	1	237
Habitability	Consumables for up to N sols (4.02 kg/person/sol + 97.57)	Per sol	-	0	-	0	300 sol	4,922
Habitability	Spares and Other Logistics (2.946 kg/sol + 2112.9 kg)	Per sol	-	0	-	0	300 sol	481
Habitability	Maintenance Equipment		-	0	-	0	-	150
EVA	EVA Suit + Primary Life Support System	692.8	-	0	-	0	1	692.8
EVA	Launch-Entry Assembly Suits	104	-	0	-	0	1	104
EVA	Spares (1.73 kg/sol/crew + 796.8)	4 crew	-	0	-	0	300 sol	1,316
Mobilit	Mars Mobility Chassis	2,457	-	0	1	2,457	-	0
Mobilit	Crew Outfitting for Chassis	200	-	0	2	400	-	0
Mobilit	Pressurized Rover	6,021	-	0	1	6,021	-	0
	Allocated Science Payload	1,000	-	0	2	2,000	-	0
Transportatio	MAV (5 sol, wet)	18,868	1	18,868	-	0	-	0
Transportatio	Part of MAV Radiator	212	1	211	-	0	-	0
Transportatio	MPS Tank Cryocoolers/BAC charged to MAV	141	1	140	-	0	-	0
Transportatio	MDM-to-MAV Adapter	200	1	200	-	0	-	0
Lander Total Payload Mass (kg)				21,767		13,948		20,088
Unallocated Mass (kg)				233		8,052		1,912

Table A3 Notional MSC Crew Expedition 3 Mission Manifest

Manifested Items		Mass (kg)	CARGO-5 Exp3 Lander 1		CREW-3 Exp3 Lander 3	
			Qty.	Mass	Qty.	Mass
	Crew (each)	100	-	0	4	400
ISRU	Atmospheric Production Plant	1,032	1	1,032	-	0
ISRU	Part of ISRU radiator mass	478	1	478	-	0
ISRU	ISRU Deployment	130	1	130	-	0
Power	Kilopower, 10 kWe each	1,544	-	0	-	0
Power	Power Management and Distribution System	400	1	400	1	400
Power	Power cable (1 km) spool	70	1	70	1	70
Robotic	Crew Support Rover (1000 kg chassis + 225 kg robotic assistant)	1,225	-	0	-	0
Robotic	Cargo Hoist	600	-	0	-	0
Habitability	Logistics Module (Dual Hatch, 3500 kg capacity)	2,600	-	0	3	7,800
Habitability	Crew Descent Module	3,516	-	0	1	3,516
Habitability	Airlock Module	3,500	-	0	-	0
Habitability	Connecting Tunnel	237	1	237	1	237
Habitability	Consumables for up to N sols (4.02 kg/person/sol + 97.57)	Per sol	-	0	300 sols	4,921
Habitability	Spares and Other Logistics (2.946 kg/sol + 2112.9 kg)	Per sol	-	0		2,330
Habitability	Maintenance Equipment		-	0		191
EVA	EVA Suit + Primary Life Support System	692.8	-	0	4	692
EVA	Launch-Entry Assembly Suits	104	-	0	4	104
EVA	Spares (1.73 kg/sol/crew + 796.8)	4 crew	-	0	300 sols	1,316
Mobility	Mars Mobility Chassis	2,457	-	0	-	0
Mobility	Crew Outfitting for Chassis	200	-	0	-	0
Mobility	Pressurized Rover	6,021	-	0	-	0
	Allocated Science Payload	1,000	-	0	-	0
Transportation	MAV (5 sol, wet)	18,868	1	18,868	-	0
Transportation	Part of MAV Radiator	212	1	211	-	0
Transportation	MPS Tank Cryocoolers/BAC charged to MAV	141	1	140	-	0
Transportation	MDM-to-MAV Adapter	200	1	200	-	0
	Lander Total Payload Mass (kg)			21,967		21,977
	Unallocated Mass (kg)			33		23

Table A4 EMC Manifest for Comparison Purposes

Manifested Items		Mass (kg)	Quantities of Manifested Items									
			Expedition 1 Landers				Expedition 2 Landers			Expedition 3 Landers		
			1	2	3	4	1	2	3	1	2	3
	Crew (each)	100	-	-	-	4	-	-	4	-	-	4
ISRU	Atmospheric Production Plant	1,677	-	1	-	-	1	-	-	1	-	-
	Part of ISRU radiator mass	n/a	-	-	-	-	-	-	-	-	-	-
	ISRU Deployment	n/a	-	-	-	-	-	-	-	-	-	-
Power	Kilopower, 10 kWe each	1,544	5	-	-	-	-	-	-	-	-	-
	Power Management and Distribution System	800	1	-	-	-	-	-	-	-	-	-
	Power cable (1 km) spool	70	2	1	1	1	1	1	1	1	1	1
Robotic	Special Regions Rover	500	1	-	-	-	-	-	-	-	-	-
	Crew Support Rover	500	1	-	-	-	-	-	-	-	-	-
	Cargo Hoist	600	2	-	-	-	-	-	-	-	-	-
Habitability	Monolithic Habitat	17,218	-	-	-	1	-	-	-	-	-	-
	Logistics Module, Small	2,600	1	-	2	-	-	1	2	-	2	2
	Logistics Module, Large	3,130	-	-	-	-	-	-	-	-	-	-
	Crew Descent Module	3,000	-	-	-	-	-	-	1	-	-	1
	Airlock Module	n/a	-	-	-	-	-	-	-	-	-	-
	Connecting Tunnel	237	-	1	-	-	1	-	-	1	-	-
	Consumables for up to N sols (4.02 kg/person/sol + 97.57) (in t)	Per sol	1.6	-	-	1.6	-	2.5	2.9	-	5.5	2.5
	Spares and Other Logistics (2.946 kg/sol + 2112.9 kg) in t	Per sol	1	-	1	0.6	-	-	0.5	-	-	0.7
	Maintenance Equipment (in t)		0.1	-	-	-	-	-	0.4	-	-	0.9
EVA	EVA Suit + Primary Life Support System	173	-	-	-	4	-	-	4	-	-	4
	Launch-Entry Assembly Suits	26	-	-	-	4	-	-	4	-	-	4
	Spares (1.73 kg/sol/crew + 796.8)(in t)	4 crew	-	-	-	1.1	-	-	1.4	-	-	1.7
Mobility	Mars Mobility Chassis	n/a	-	-	-	-	-	-	-	-	-	-
	Crew Outfitting for Chassis	n/a	-	-	-	-	-	-	-	-	-	-
	Pressurized Rover	6,452	-	-	1	-	-	1	-	-	-	-
	Mars Surface Transporter	1,890	1	-	1	-	-	-	-	-	-	-
Science	Allocated Science Payload	1,000	-	-	1	-	-	-	1	-	-	1
	Science Laboratory	3,000	1	-	-	-	-	-	-	-	-	-
Transportation	MAV (1 sol, wet)	18,016	-	1	-	-	1	-	-	1	-	-
	Part of MAV Radiator	n/a	-	-	-	-	-	-	-	-	-	-
	MPS Tank Cryocoolers/BAC charged to MAV	n/a	-	-	-	-	-	-	-	-	-	-
	MDM-to-MAV Adapter	n/a	-	-	-	-	-	-	-	-	-	-
Unallocated Mass (kg)			**44**				**12,779**			**12,980**		

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